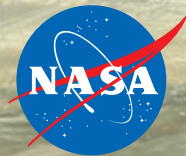


Cassini In-Flight Navigation Adaptations

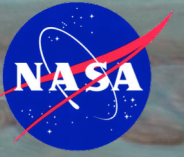


Jet Propulsion Laboratory
California Institute of Technology

Duane Roth

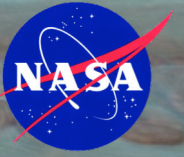
Yungsun Hahn, William Owen, Sean Wagner

Agenda



- Brief History of Mission
- Adaptation Drivers and Types
- Examples
 - Trajectory Design
 - Orbit Determination
 - Optical Navigation
 - Flight Path Control
 - Software
- Conclusions

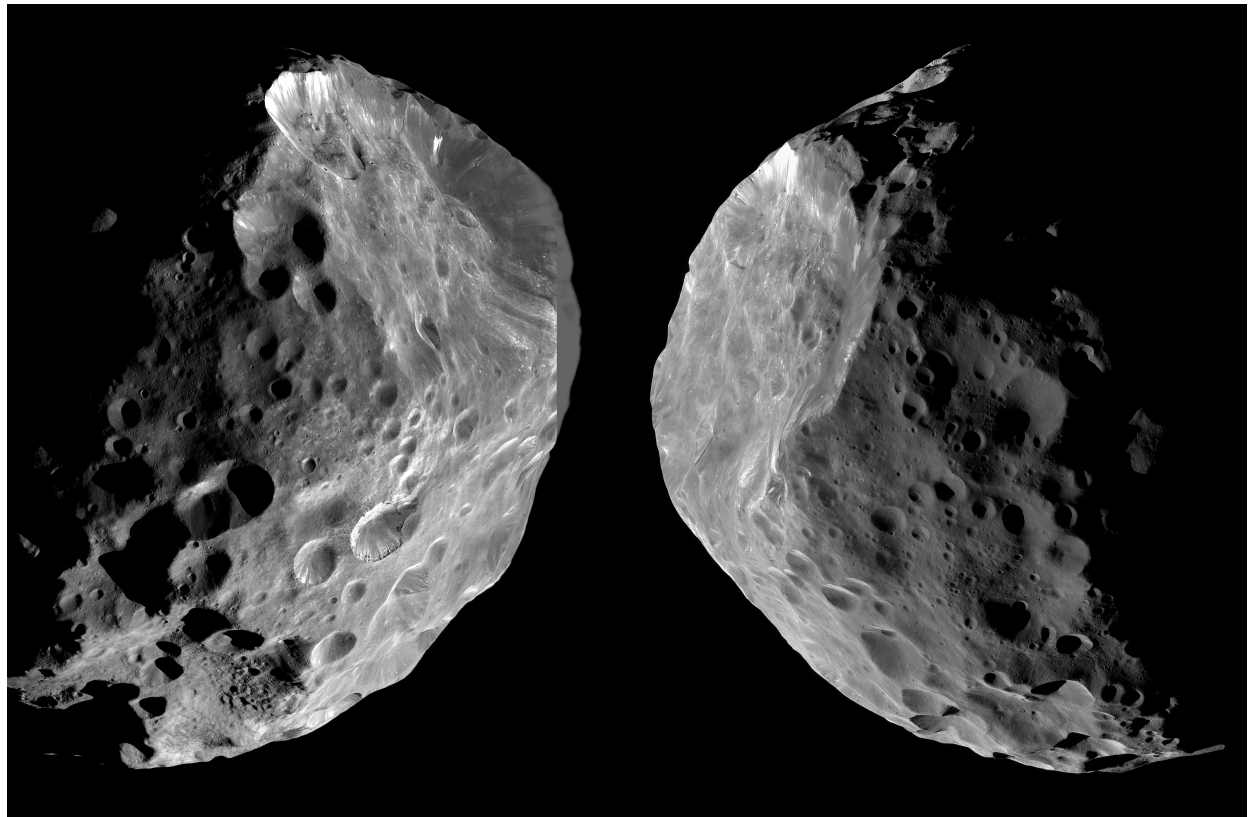
Brief History of Cassini Mission



- Goal: study the composition and structure of Saturn's atmosphere, magnetosphere, rings, and satellites.
- Launched October 15, 1997
 - VVEJGA trajectory
 - Arrived Saturn July 1, 2004

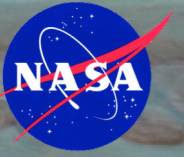


May 31, 2018

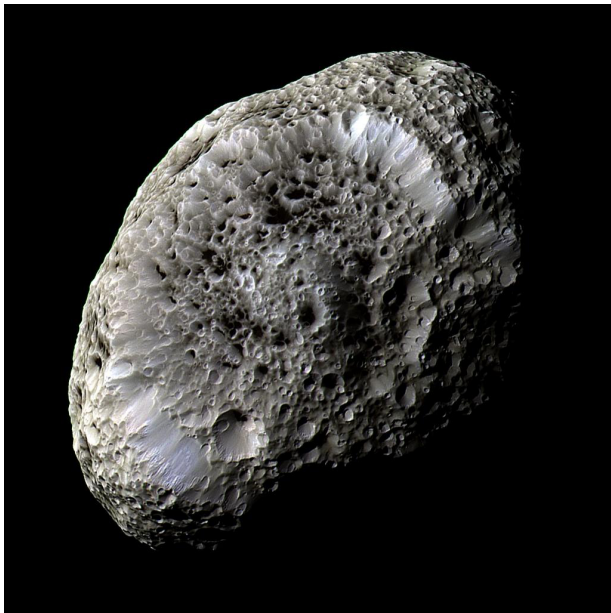


SpaceOps 2018

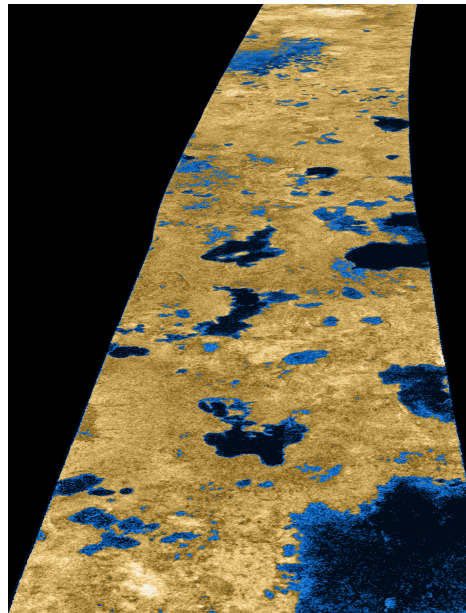
Brief History of Cassini Mission



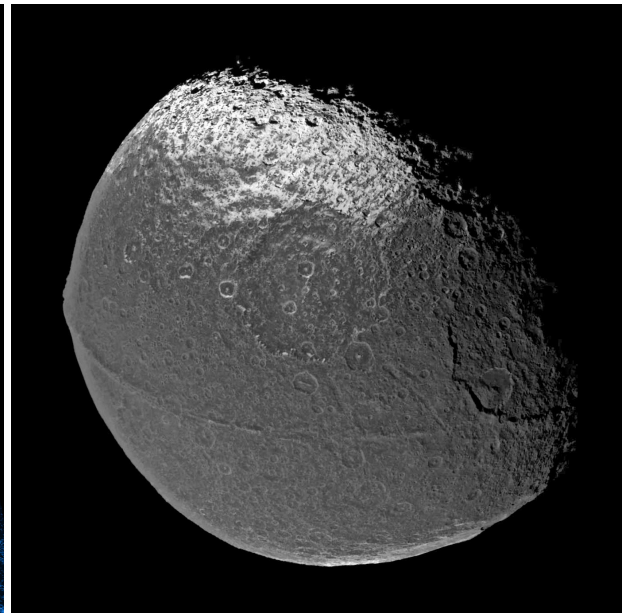
- Goal: study the composition and structure of Saturn's atmosphere, magnetosphere, rings, and satellites.
- Orbital tour includes prime and two extended missions, together spanning almost half of Saturn orbit.
 - 4 year **Prime Mission** to September 2008
 - Huygens probe release and landing on Titan
 - 54 targeted flybys
 - 46 Titan, 4 Enceladus, 1 each of Dione, Rhea, Hyperion, Iapetus



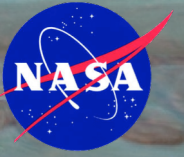
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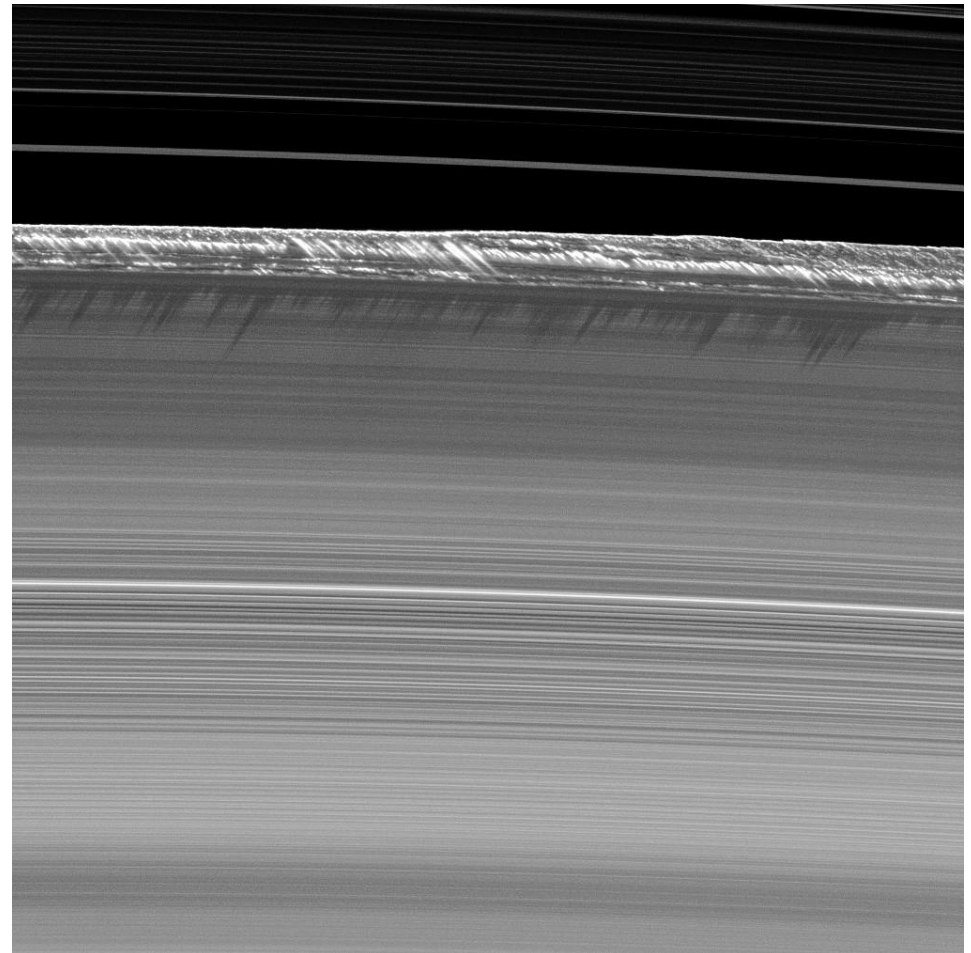
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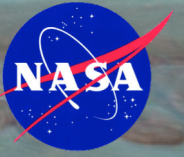
Brief History of Cassini Mission



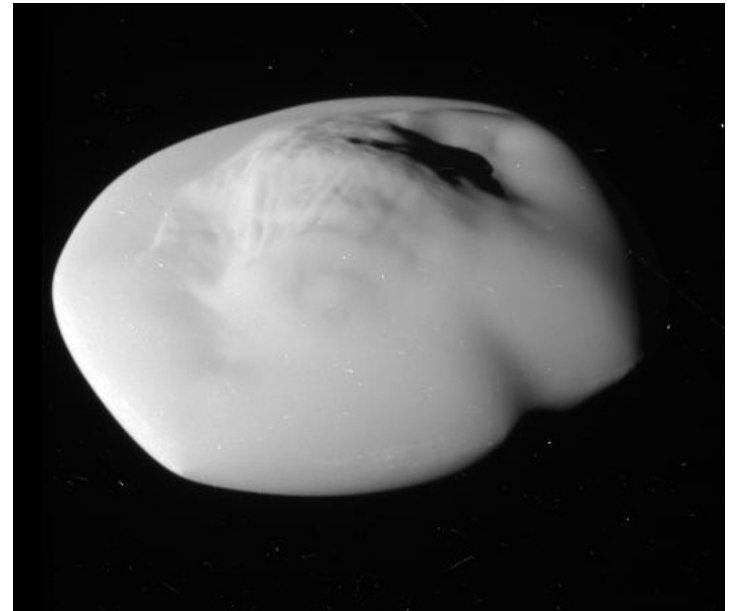
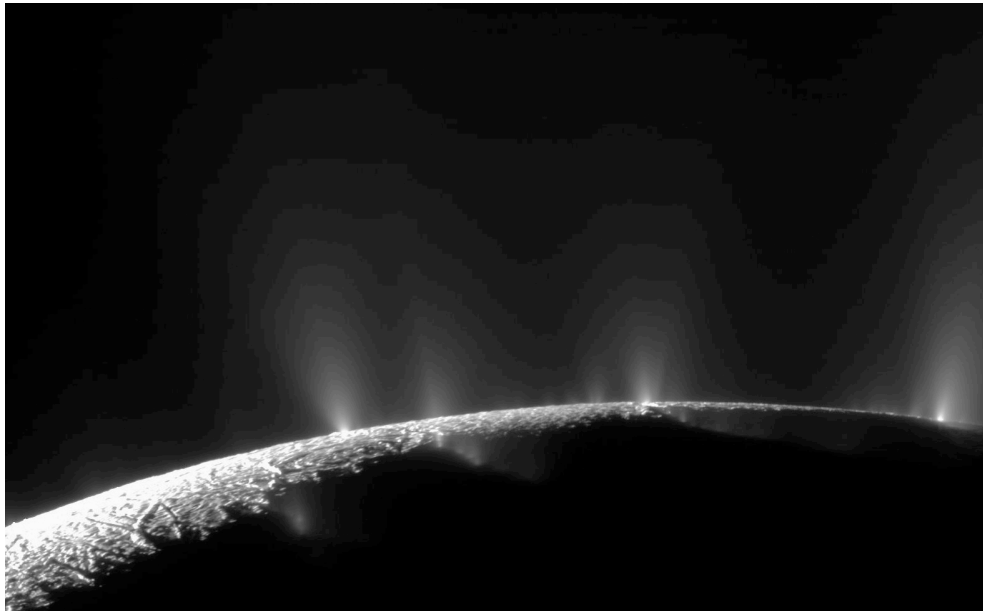
- Goal: study the composition and structure of Saturn's atmosphere, magnetosphere, rings, and satellites.
- Orbital tour includes prime and two extended missions, together spanning almost half of Saturn orbit.
- 2 year **Equinox Mission** to September 2010
 - Further Enceladus investigations
 - 36 targeted flybys
 - 27 Titan, 7 Enceladus, 1 each of Rhea, Dione



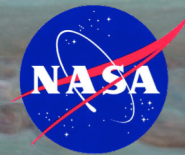
Brief History of Cassini Mission



- Goal: study the composition and structure of Saturn's atmosphere, magnetosphere, rings, and satellites.
- Orbital tour includes prime and two extended missions, together spanning almost half of Saturn orbit.
 - 7 year **Solstice Mission** to Saturn atmospheric entry on September 15, 2017
 - Observe seasonal changes, more Enceladus investigations, F-ring orbits, Grand Finale
 - 70 targeted flybys
 - 54 Titan, 11 Enceladus, 3 Dione, 2 Rhea

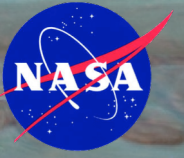


Adaptation Drivers & Types



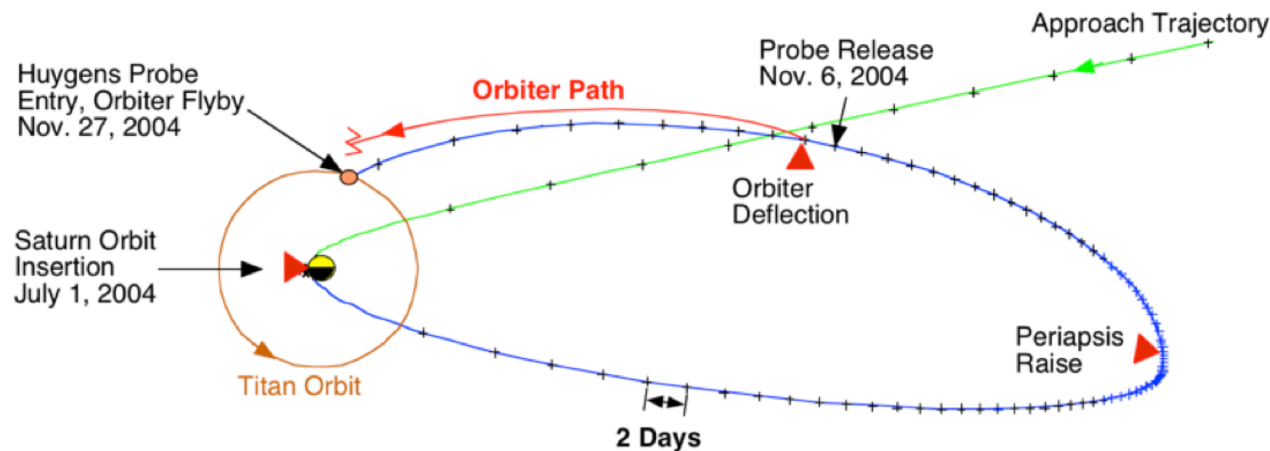
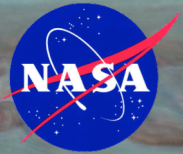
- Adapting operational processes is nothing new. What distinguishes Cassini is the long duration mission with ever-changing orbital geometries.
 - Altogether, Cassini flight operations lasted nearly 20 years. Orbital operations spanned 13 years.
 - Orbital characteristics altered via gravity assists to meet mission objectives.
- Adaptations included to:
 - More efficiently fly mission
 - Enable further investigation of science discoveries
 - Fine tune existing science observations
 - Reduce observational and mission risks
 - Respond to anomalous behavior
- Adaptations categorized according to navigation sub-system functions
 - Trajectory design
 - Orbit determination
 - Optical navigation
 - Flight path control
 - Software development

Trajectory Design Adaptations



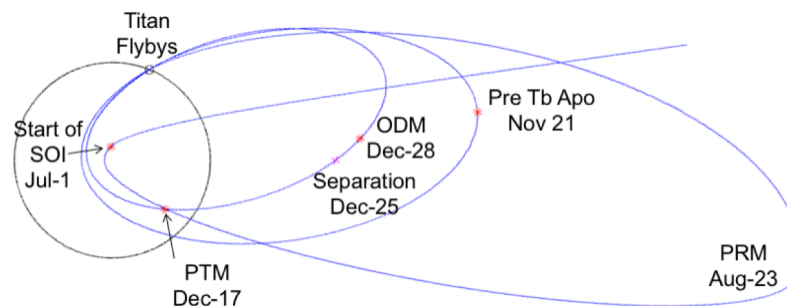
- Trajectory design adaptations were implemented through reference trajectory updates.
 - Many early updates driven by accuracy improvements in knowledge of satellite ephemeris, Saturn system parameters and atmosphere/debris environment.
 - Re-optimize trajectory for efficiency – keep ΔV costs low.
 - Raise minimum Titan altitudes to reduce tumbling risk from Titan's denser than expected atmosphere.
 - Raise third targeted Enceladus flyby altitude to reduce debris hazard risk from newly discovered plume.
 - Others added, recovered, or improved science observations.
 - **Huygens probe redesign**
 - Addition of 'targeted quality' Tethys flyby
 - De-conflict observations around only Iapetus targeted encounter
 - Change maneuver locations in conflict with science observations

Huygens Probe Redesign



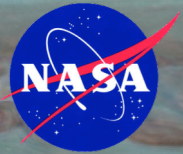
- Design flaw discovered in Huygens receiver onboard the Cassini orbiter — bandwidth was too small to accommodate the Doppler shift of the relay signal.
 - Doppler shift was reduced by raising the altitude of the orbiter during the probe delivery encounter from 1200 km to 60000 km.
 - Changes isolated to between SOI and T3 to protect downstream science observations.
 - Probe delivery at Titan C instead of Titan 1.

Further complications:
Iapetus flyby

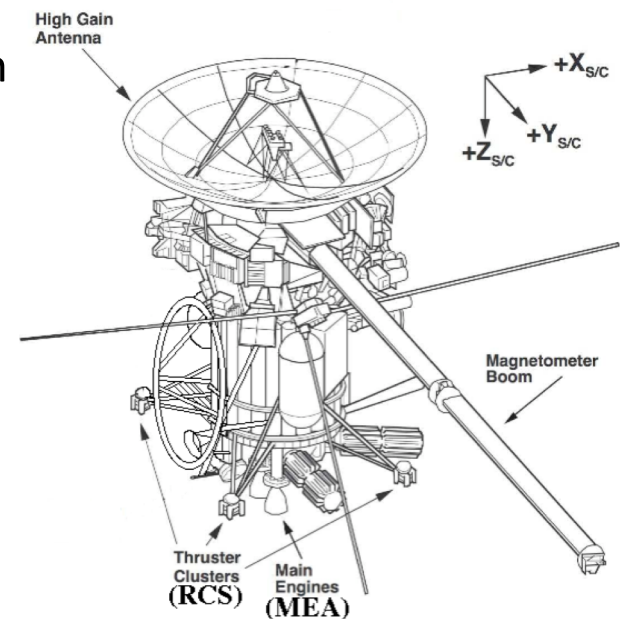
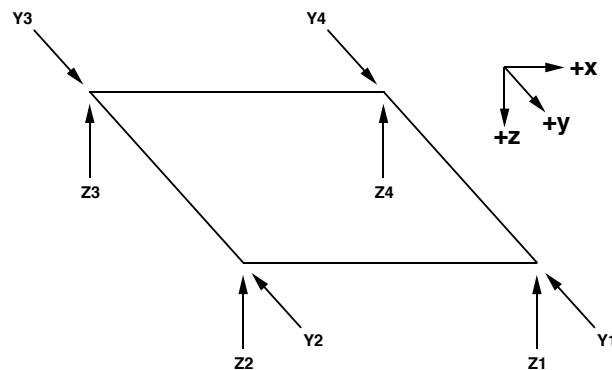


Redesign Cost: 87 m/s

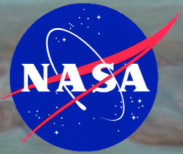
Orbit Determination Adaptations



- Orbit determination adaptations resulted from changes in the spacecraft operational environment and processes.
 - Routine
 - Spacecraft orientation modeling – sun pointed or other?
 - Attitude control mode – thrusters or wheels?
 - Improve orbit determination accuracy
 - Calibration of high resolution ΔV telemetry
 - Used for filter a priori configuration
 - Huygens probe Iapetus flyby
 - Monitor spacecraft for signs of degradation
 - Y-thruster calibrations



Huygens Probe Iapetus Flyby

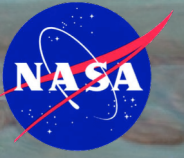


- Perturbation to Cassini orbit from Iapetus close flyby put Huygens' entry flight path angle requirement at risk.
 - Mitigation not only by changing trajectory, but also by campaign to improve estimate of Iapetus' mass.
 - GM estimate with error smaller than $7.2 \text{ km}^3/\text{s}^2$ was needed to meet entry angle requirement. Estimates varied by as much as $16 \text{ km}^3/\text{s}^2$.
 - Efforts focused on a 1.1 million km flyby of Iapetus nine days before Titan-a.
 - Spacecraft kept in quiet mode
 - Interferometric measurements scheduled using NRAO's Very Long Baseline Array
 - Additional radiometric data scheduled
 - Improved estimate of Saturn barycenter after Ta, Tb also improved Iapetus mass estimate.
 - Value determined prior to probe entry was $120.55 \pm 0.79 \text{ km}^3/\text{s}^2$. Current best estimate is $120.5038 \pm 0.0080 \text{ km}^3/\text{s}^2$.

- Ephemeris accuracies obtained through radiometric sensing of the satellite gravitational signature from multiple close flybys eventually surpassed that from opnavs.
 - Titan opnavs, the least accurate, discontinued first
 - Titan's atmosphere inhibits accurate centerfinding.
 - Opnavs of other large icy satellites continued to be necessary
 - Prevent long-term runoff in along-track direction
 - Scheduled at a much lower rate
 - Placement in SSR critical playback partition unnecessary.
 - Images selected to reveal position errors in the satellite along-track direction

- Flight path control adaptations are included to fly the mission more efficiently and improve predictions of downstream maneuver magnitudes.
 - **Target biased aimpoints**
 - Identify and mitigate backup maneuver locations with excessive ΔV cost
 - Backup maneuvers not examined in statistical analyses
 - When prime is deterministically large and close to periapsis
 - Identify in advance and uplink early
 - Prepare for significant changes to downstream targets
 - When backup maneuver transfer is singular (pi-transfer)
 - Allow target to float
 - Use history of past maneuvers to improve maneuver execution error model.
 - Long duration mission with many 'samples' enables data driven model.

Target Biased Aimpoints



- Targets generally only changed as a result of reference trajectory updates
- Biases introduced for some flybys by flight path control analysts to more efficiently fly the mission
 - OD accuracy improved as Saturn system errors reduced and ΔV s from attitude control became better predicted
 - Maneuver execution errors reduced by fine tuning burn termination times
 - Improved accuracies allow smaller target corrections to be confidently implemented.
- Biased trajectories reviewed before implementation by science team
- Target time and B-plane coordinates biased, depending on goal

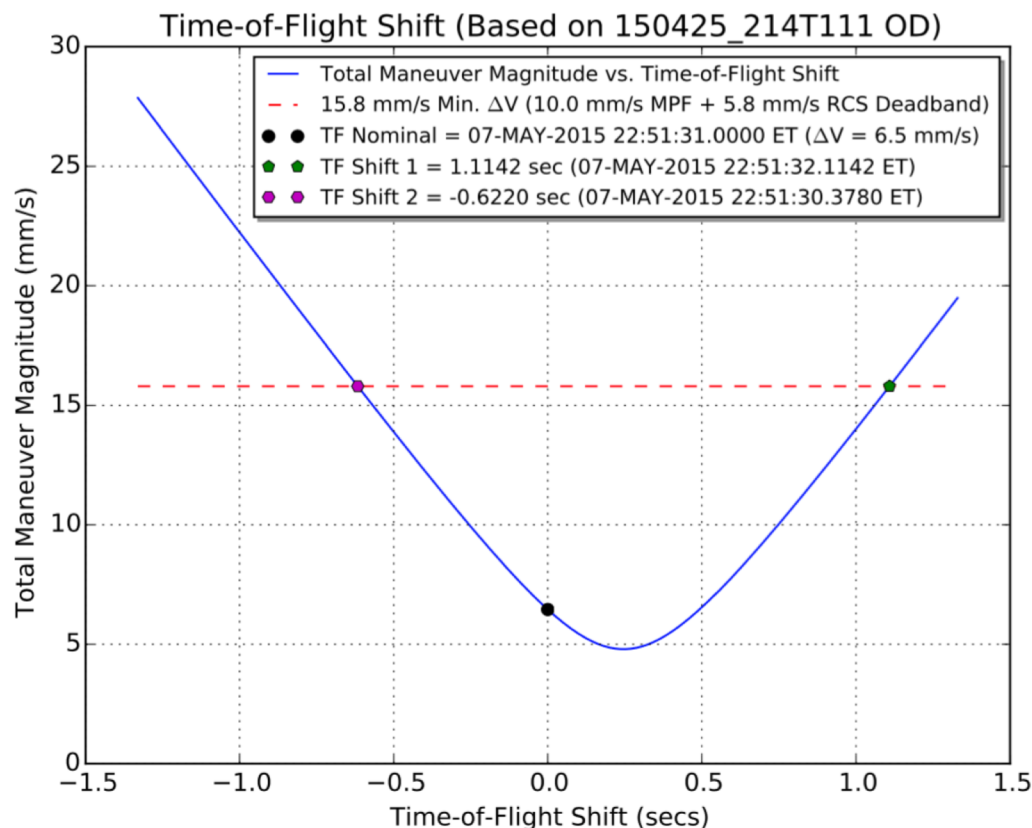
Biasing Target Time



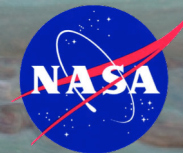
- Biasing the target time is implemented when correction is desired, but maneuver needed to accomplish correction is too small
 - Smallest realizable maneuver allowed by project management was 15.8 mm/s
 - Time biasing enables attainment of desired gravity assist ΔV

OTM409 provides example:

- Initial cost of 6 mm/s for 1.2 km B-plane correction and -0.4 seconds in TCA
- Downstream cost of canceling maneuver is 440 mm/s
- With time bias of 0.7 seconds, downstream cost reduced to 40 mm/s
- ΔV savings is 400 mm/s



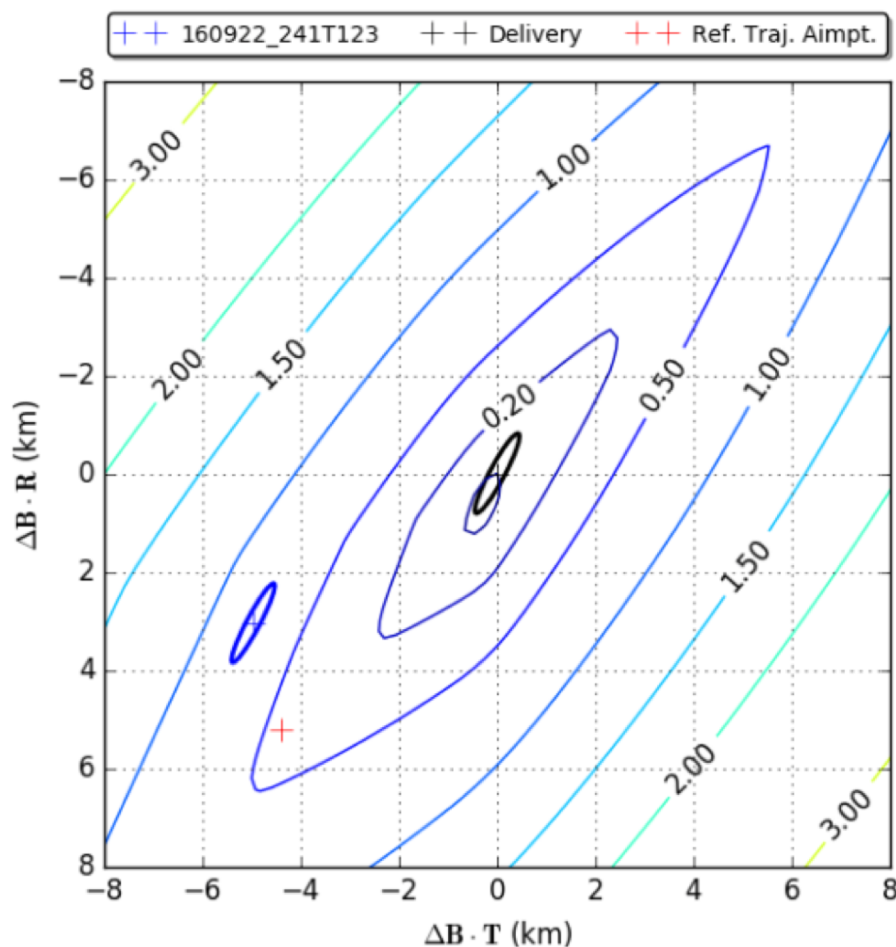
Biassing B-plane Coordinates



- Cumulative effect of small errors and canceled or backup maneuvers caused the operational trajectory to deviate from the reference trajectory over time
- Deviations eventually become large enough that future targets become noticeable non-optimal

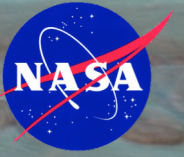
OTM460 provides example

- Initial cost of 6.8 mm/s for reference trajectory target
- Choosing optimal B-plane target reduces downstream cost by 350 mm/s
- Increases maneuver magnitude to 24.5 mm/s. Time bias not needed.



- Maneuver Automation Software developed during cruise operations to reduce duration needed between final OD design and availability of ready-to-uplink maneuver commands
 - Only 24 maneuvers scheduled in nearly seven years of interplanetary cruise
 - 5 day process
 - 3 maneuvers scheduled in 16 days common in orbital operations
 - As little as 5 hour process with MAS
- Fortran based legacy navigation software replaced with new C++ based software
 - Transition preceded with two year development, test, and checkout period

Conclusions



- The Cassini Navigation Team successfully took advantage of improvements in knowledge, procedures, and the computing environment
 - All requirements met
 - Two extended missions enabled
- Future projects will benefit from Cassini legacy
 - Improved ephemerides of Saturn and its satellites
 - Techniques developed by Cassini will be used by future projects